Virtual Memory:
Anatomy of a memory reference

Questions Answered in this Lecture:

- How do we get illusion of the full address space?
- How do we swap out pages to disk efficiently?
- *Which* pages do we swap out?
- What is *thrashing?*
- What does an actual memory reference look like?
- How does the OS detect NULL pointer derefs?

Announcements

- P2a due Thursday! No extensions this time!
- We won’t be making exceptions for bad git commits/stashes/etc. moving forward

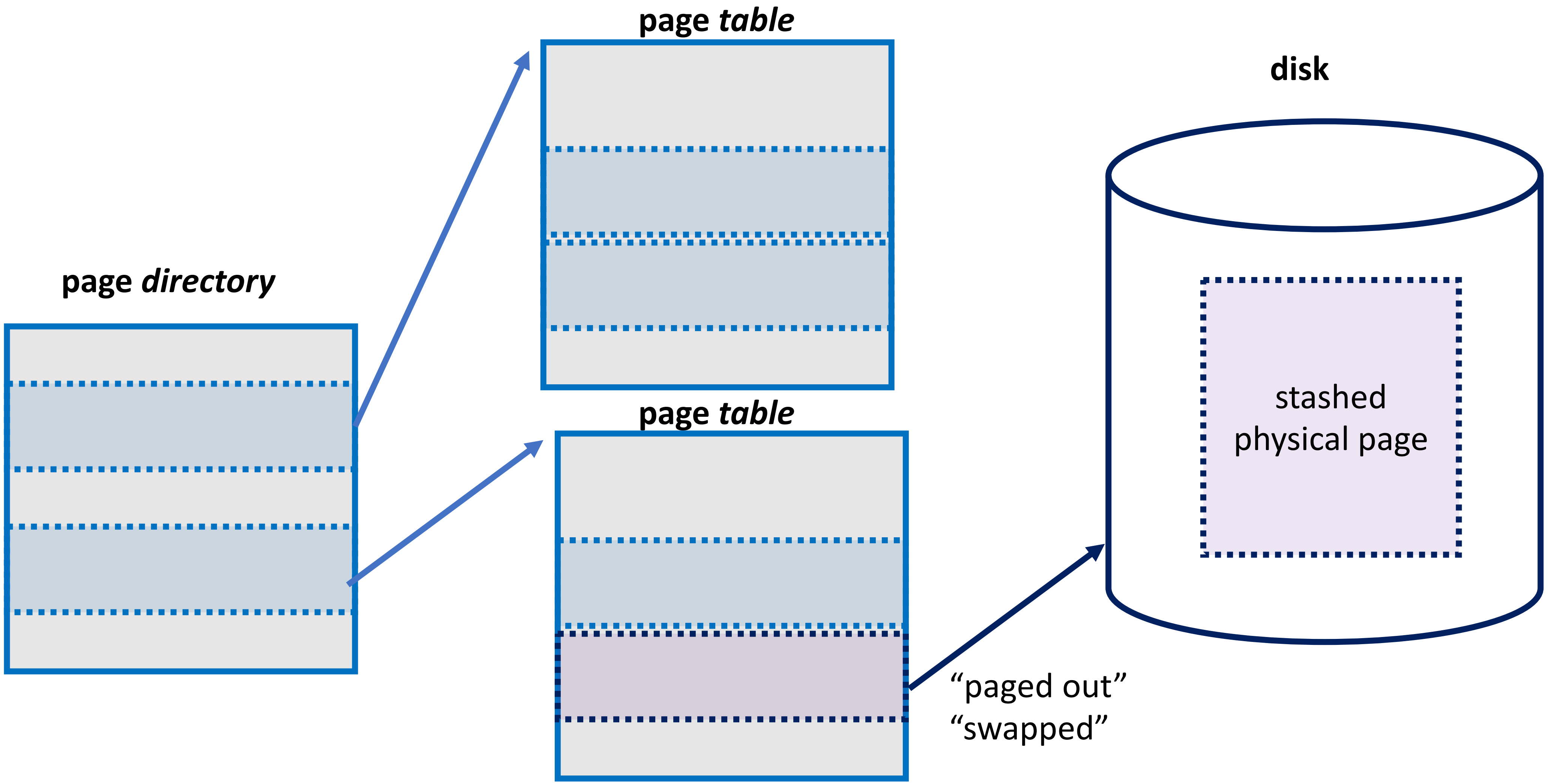
Virtualizing Memory

- Remember, we're giving the illusion of an ***address space***
- This is a *great* abstraction because ***we provide that there are bytes named by addresses***…
- But ***from where those bytes come*** is hidden to the user
- Recall:
  - phys addr space: bytes can come from RAM, ROM, memory controller, PCI device, SCSI device, etc.

Where do the bytes come from?

- **Default case**: a physical page of RAM
- What if we're running low on RAM?

Use Disk!

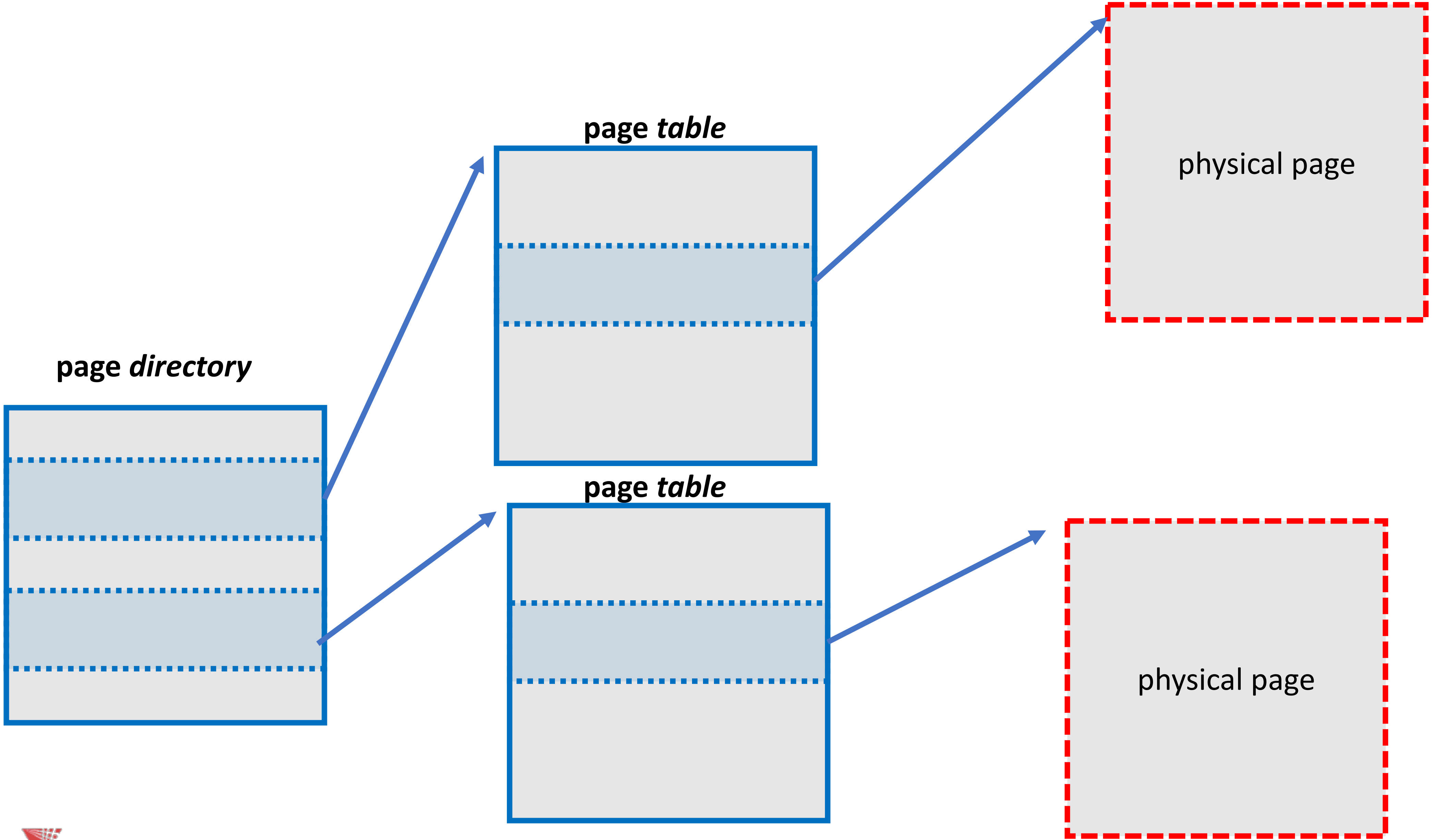

page table
disk
page directory
page table
stashed
physical page
“paged out”
“swapped”

What does this mean?

- We need some way to tie PTEs to disk (we’ll come back to this)
- Can’t just use a physical address!
- Need to integrate paging code with block (disk) driver

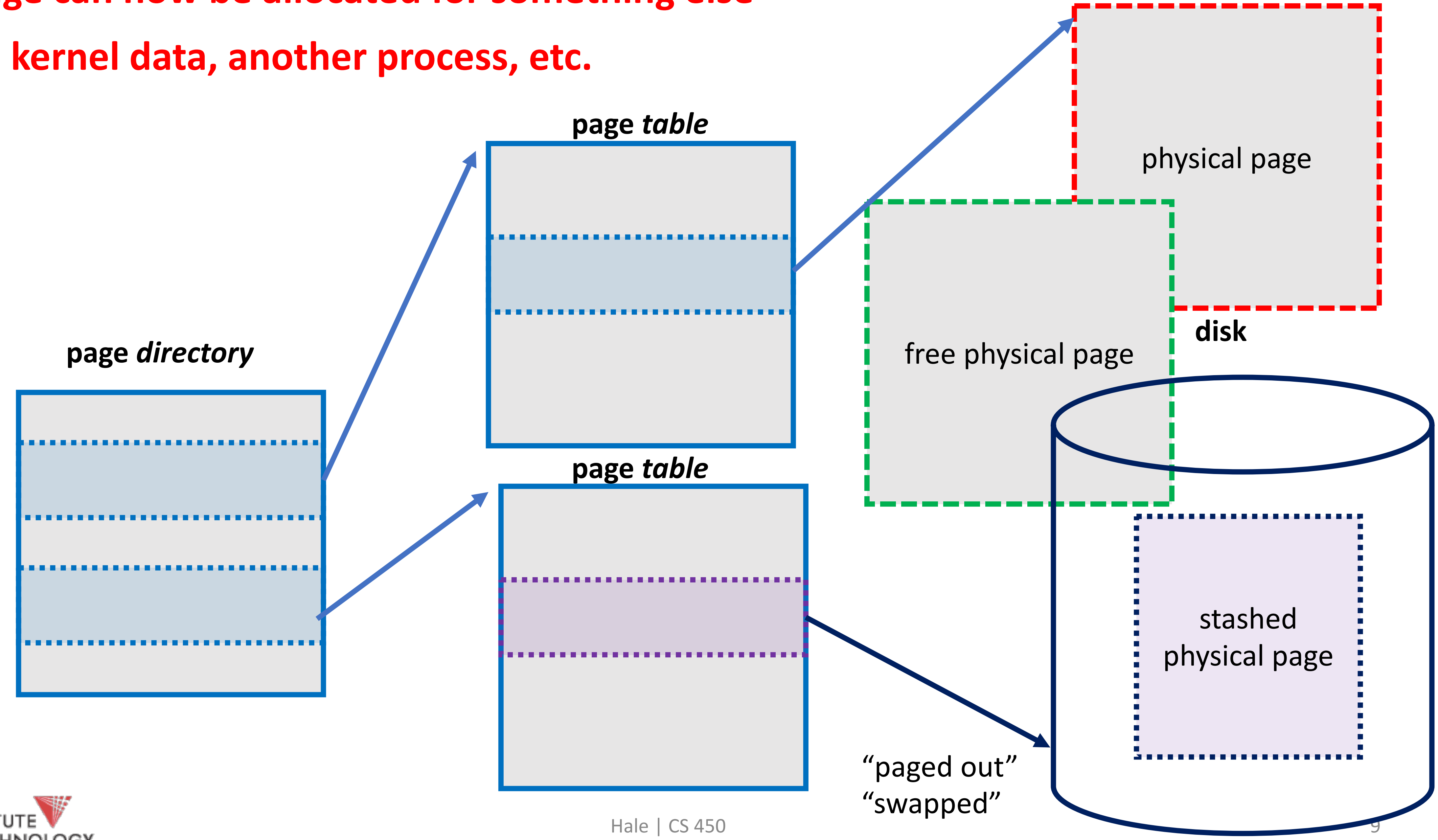
Swapping

- Now if we're running low on memory, we pick a victim process, and throw some of its pages out to disk
- We ***stash a pointer to the disk blocks***, make a record of it
- Then invalidate the old PTE


page **table**
physical page
page **directory**
page **table**
physical page

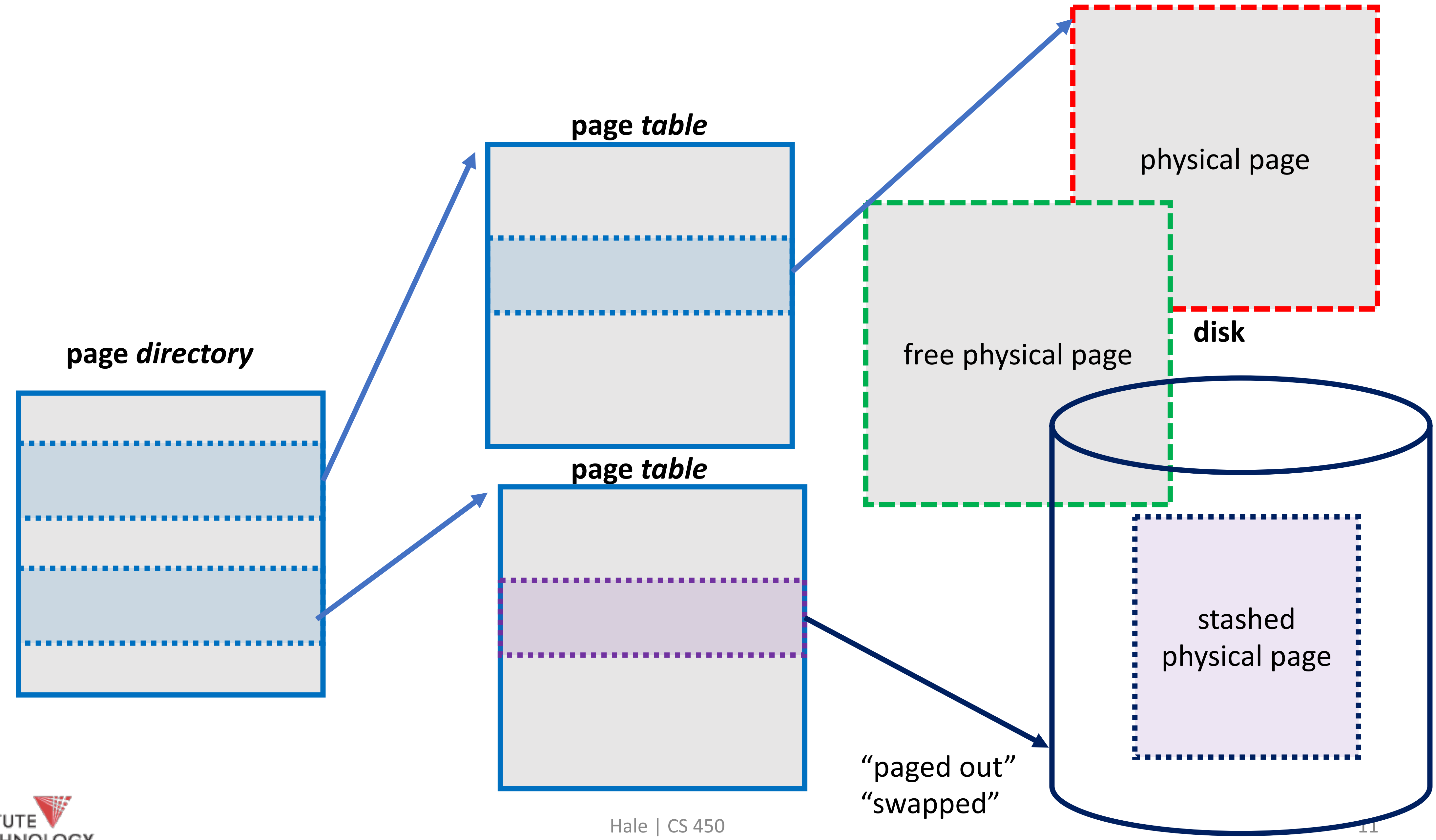
this page can now be allocated for something else

e.g. kernel data, another process, etc.



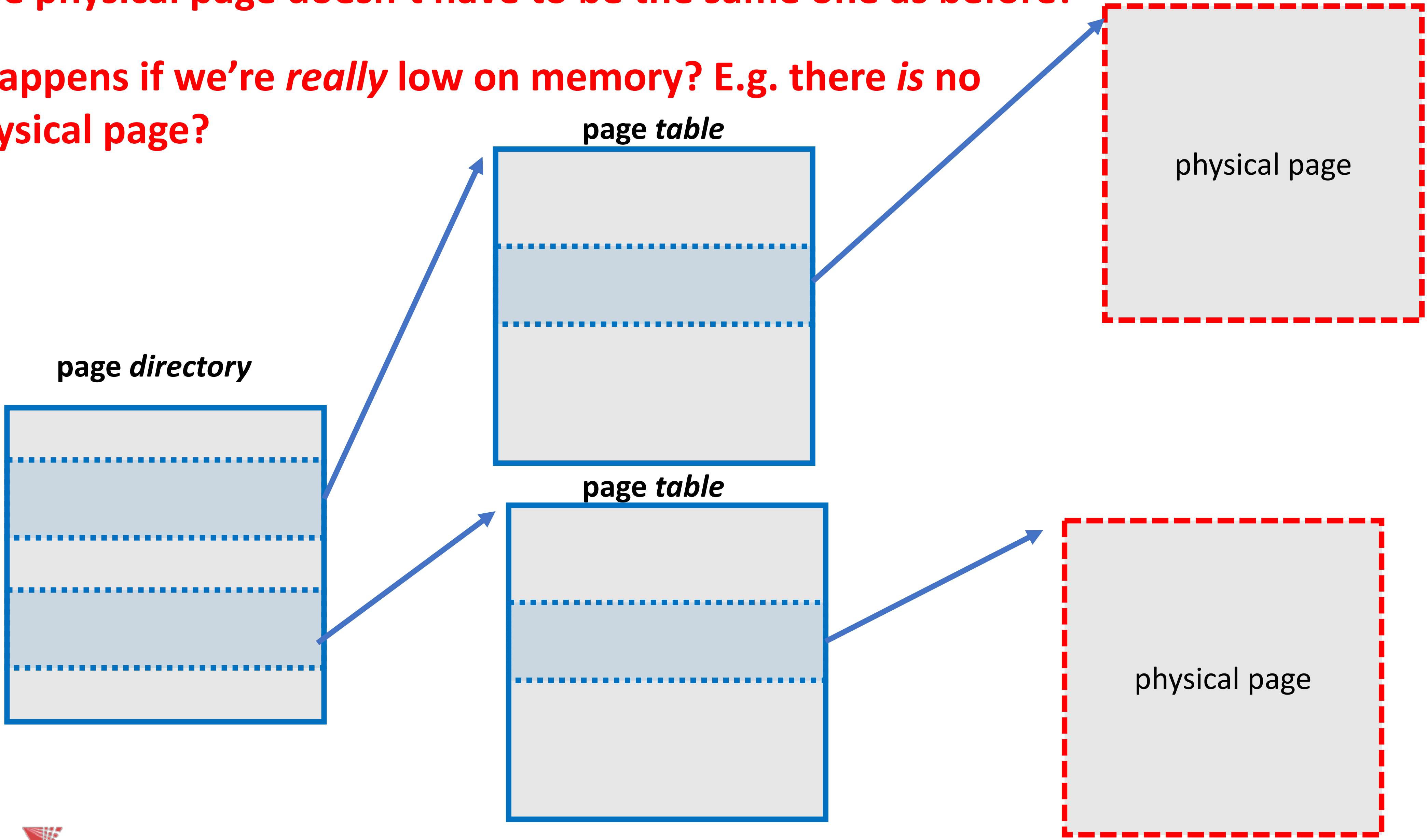
What if we need the page?

- Process tries to access the old VA again. What happens?


page directory
page table
page table
physical page
free physical page
disk
stashed
physical page
"paged out"
"swapped"

This free physical page doesn't have to be the same one as before!

What happens if we're *really* low on memory? E.g. there *is* no free physical page?



Thrashing

- When there are no free pages, we’re constantly swapping out to disk
- E.g., take a page from one process, give it to another, and so on
- Very bad place to be. Cache won’t help here.
- Buy more RAM!

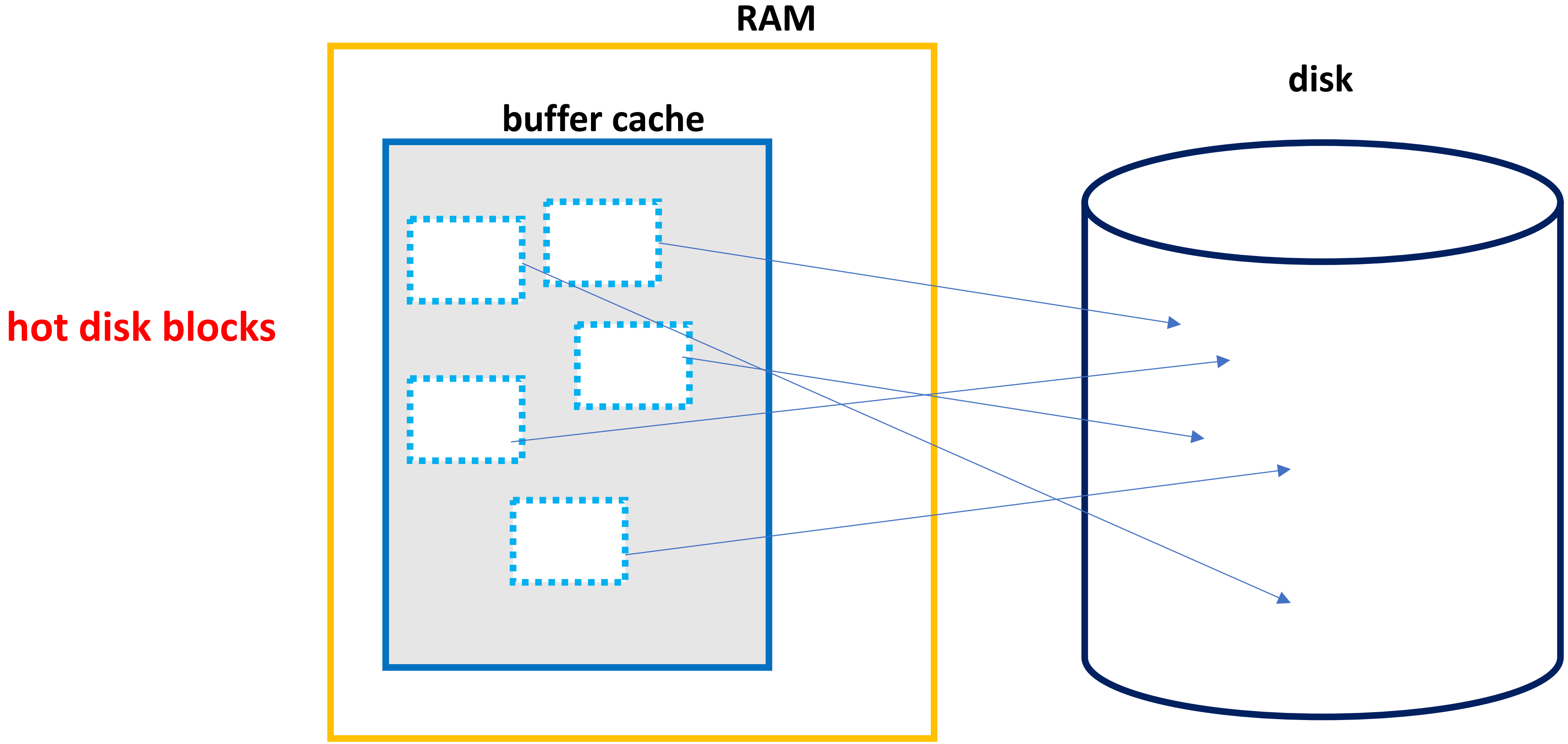
Page replacement (policy)

- Which page to replace?
- FIFO (oldest mapped page is the target)
- LRU (least recently used. how to keep track?)
- Random

Disk is slow

- Spinning disks especially are very slow!
- We want to minimize how much we go off to disk
- What do we do?

The *buffer cache*



```
swap_in (block_no) {
     blk = block_lookup(block_no, buffer_cache)
     if (blk == NULL) { // MISS
          blk = disk_read(block_no);
     }
     page = page_alloc();
     copy(page, blk);
     return page;
}
```

Anatomy of a memory reference

Or, how does mapping work?

```
subutai.cs.iit.edu ➜  450  cat bad_ptr.c
#include <stdio.h>
#include <stdlib.h>


int main (int argc, char ** argv) {

    unsigned long * a_ptr = (unsigned long*)0xdeadbeefULL;

    *a_ptr = 0x1234;

    return 0;
}
```

```
0000000000401020 <main>:
  401020:       b8 ef be ad de          mov    $0xdeadbeef,%eax
  401025:       48 c7 00 34 12 00 00    movq   $0x1234,(%rax)
  40102c:       31 c0                   xor    %eax,%eax
  40102e:       c3                      retq
  40102f:       90                      nop
```

This is our memory reference

```
subutai.cs.iit.edu ➜  450  ./bad_ptr
[1]    5433 segmentation fault (core dumped)  ./bad_ptr
```

why?

how?

```
subutai.cs.iit.edu ➜ 450  cat good_ptr.c
#include <stdlib.h>
#include <stdio.h>

#define PAGE_SIZE 4096

int main (int argc, char ** argv) {

    unsigned long * good_ptr = (unsigned long*)malloc(PAGE_SIZE);

    *good_ptr = 0x1234;

    printf("%lu\n", *good_ptr);

    return 0;
}
```

```
0000000000401136 <main>:
  401136:       55                      push   %rbp
  401137:       48 89 e5                mov    %rsp,%rbp
  40113a:       48 83 ec 20             sub    $0x20,%rsp
  40113e:       89 7d ec                mov    %edi,-0x14(%rbp)
  401141:       48 89 75 e0             mov    %rsi,-0x20(%rbp)
  401145:       bf 00 10 00 00          mov    $0x1000,%edi
  40114a:       e8 f1 fe ff ff          callq  401040 <malloc@plt>
  40114f:       48 89 45 f8             mov    %rax,-0x8(%rbp)
  401153:       48 8b 45 f8             mov    -0x8(%rbp),%rax
  401157:       48 c7 00 34 12 00 00    movq   $0x1234,(%rax)
  40115e:       48 8b 45 f8             mov    -0x8(%rbp),%rax
  401162:       48 8b 00                mov    (%rax),%rax
  401165:       48 89 c6                mov    %rax,%rsi
  401168:       bf 10 20 40 00          mov    $0x402010,%edi
  40116d:       b8 00 00 00 00          mov    $0x0,%eax
  401172:       e8 b9 fe ff ff          callq  401030 <printf@plt>
  401177:       b8 00 00 00 00          mov    $0x0,%eax
  40117c:       c9                      leaveq
  40117d:       c3                      retq
  40117e:       66 90                   xchg   %ax,%ax
```

```
subutai.cs.iit.edu ➜ 450  cat evil.c
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>

int main (int argc, char ** argv) {
    unsigned long * clever = (unsigned long*) 0x405000ULL;
    void * a = malloc(10); // make sure we have a heap

    *clever = 0x1234;
    printf("Gotcha!\n");
    return 0;
}
```

```
subutai.cs.iit.edu ➜ 450  ./evil
Gotcha!
```

```
subutai.cs.iit.edu ➜ 450  cat /proc/11152/maps
00400000-00401000 r--p 00000000 08:11 49285371                           /home-remote/kyle/450/evil
00401000-00402000 r-xp 00001000 08:11 49285371                           /home-remote/kyle/450/evil
00402000-00403000 r--p 00002000 08:11 49285371                           /home-remote/kyle/450/evil
00403000-00404000 r--p 00002000 08:11 49285371                           /home-remote/kyle/450/evil
00404000-00405000 rw-p 00003000 08:11 49285371                           /home-remote/kyle/450/evil
00405000-00426000 rw-p 00000000 00:00 0                                  [heap]
7ffff7de5000-7ffff7e07000 r--p 00000000 fd:00 8395967                    /usr/lib64/libc-2.28.so
7ffff7e07000-7ffff7f54000 r-xp 00022000 fd:00 8395967                    /usr/lib64/libc-2.28.so
7ffff7f54000-7ffff7fa0000 r--p 0016f000 fd:00 8395967                    /usr/lib64/libc-2.28.so
7ffff7fa0000-7ffff7fa1000 ---p 001bb000 fd:00 8395967                    /usr/lib64/libc-2.28.so
7ffff7fa1000-7ffff7fa5000 r--p 001bb000 fd:00 8395967                    /usr/lib64/libc-2.28.so
7ffff7fa5000-7ffff7fa7000 rw-p 001bf000 fd:00 8395967                    /usr/lib64/libc-2.28.so
7ffff7fa7000-7ffff7fad000 rw-p 00000000 00:00 0
7ffff7fcd000-7ffff7fd0000 r--p 00000000 00:00 0                          [vvar]
7ffff7fd0000-7ffff7fd2000 r-xp 00000000 00:00 0                          [vdso]
7ffff7fd2000-7ffff7fd3000 r--p 00000000 fd:00 8395883                    /usr/lib64/ld-2.28.so
7ffff7fd3000-7ffff7ff3000 r-xp 00001000 fd:00 8395883                    /usr/lib64/ld-2.28.so
7ffff7ff3000-7ffff7ffb000 r--p 00021000 fd:00 8395883                    /usr/lib64/ld-2.28.so
7ffff7ffc000-7ffff7ffd000 r--p 00029000 fd:00 8395883                    /usr/lib64/ld-2.28.so
7ffff7ffd000-7ffff7ffe000 rw-p 0002a000 fd:00 8395883                    /usr/lib64/ld-2.28.so
7ffff7ffe000-7ffff7fff000 rw-p 00000000 00:00 0
7ffffffde000-7ffffffff000 rw-p 00000000 00:00 0                          [stack]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

Representing address space *regions*

```
struct mem_region {
    unsigned long start;
    unsigned long len;
    int type;
    int present;
    int paged_out;
    …
}
```

Starting a process

- Kernel constructs memory regions for initial regions (***stack, heap, kernel***)
- All other portions of the address space are ***unmapped***
- New regions must be created ***by request*** from userspace (`mmap()`)

What happens on a page fault?

- Lookup faulting address in the ***region map***
  - Some kind of search data structure: hash table, binary search tree, linked list, etc.
- Hit? Something special (like swapped page) is going on
- Miss? This is an address that isn't mapped. SEGFAULT

```
char *map = mmap(0, textsize, PROT_READ | PROT_WRITE, MAP_SHARED, fd, 0);
```

how does this work?

Summary

- Disk allows us to better support illusion of full address space (swapping)
- Kernel backs address space regions with metadata (mechanism)
- Page faults drive the whole thing